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Remote Sensing of Sulfur Dioxide Effects on Vegetation: Spectroradiometry

Tennessee Valley Authority
Muscle Shoals, AL

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Remote Sensing of Sulfur Dioxide Effects on Vegetation—Spectroradiometry

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Remote measurements of spectral reflectance were made in a laboratory to study sulfur dioxide (SO_2) effects on the foliage of soybean [Glycine max (L.) Merr.] and winter wheat (Triticum aestivum) plants. The relationship between spectral reflectance and foliar injury from SO_2 was analyzed by separating injury into its components—chlorosis and necrosis—and reflectance into bands within the visible and near-infrared spectra. Results indicate that, for winter wheat, total visible reflectance as well as individual wavelength bands could be used to distinguish the SO_2 effects. Three classes of chlorosis and four classes of necrosis, based on severity, could be distinguished by their visible reflectance characteristics. These results indicate that remote sensors that measure visible reflectance may be able to distinguish moderate to severe injury to wheat from low altitudes. Scans of soybeans provided less positive results. There was no statistically significant (α = .05) difference among the means of blue, green, red, or near-infrared reflectance or the IR/R ratio when unaffected and chlorotic soybean classes were compared. However, significant (α = .05) differences in the means of green, red, and near-infrared reflectance (but not blue and the IR/R ratio) were found when unaffected and moderately to severely necrotic soybean classes were compared. Evidently, unless the SO_2 injury to soybeans involves necrosis, reflectance-measuring remote sensors are not likely to detect it from even a low-flying (~500 m above ground level) airborne platform. The necrosis symptom is generally associated with severe levels of foliar injury, whereas chlorosis usually predominates at moderate and light levels.

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ABSTRACT

Remote measurements of spectral reflectance were made in a laboratory to study sulfur dioxide (SO_2) effects on the foliage of soybean [Glycine max (L.) Merr.] and winter wheat (Triticum aestivum) plants. Spectral scanning provides guidance for pre-mission selection of appropriate optical filters for aerial multiband cameras and channel combinations for multispectral scanners.

The relationship between spectral reflectance and foliar injury from SO_2 is complex. It was analyzed by separating injury into its components--chlorosis and necrosis--and reflectance into bands within the visible and near-infrared spectra. Results indicate that, for winter wheat, total visible reflectance as well as individual wavelength bands could be used to distinguish the SO_2 effects. Three classes of chlorosis and four classes of necrosis, based on severity, could be distinguished by their visible reflectance characteristics. These results indicate that remote sensors that measure visible reflectance may be able to distinguish moderate to severe injury to wheat from low altitudes.

Scans of soybeans provided less positive results. There was no statistically significant ($\alpha = .05$) difference among the means of blue, green, red, or near infrared reflectance or the IR/R ratio when unaffected and chlorotic soybean classes were compared. However, significant ($\alpha = .05$) differences in the means of green, red, and near-infrared reflectance (but not blue and the IR/R ratio) were found when unaffected and moderately to severely necrotic soybean classes were compared. Evidently, unless the SO_2 injury to soybeans involves necrosis, reflectance-measuring remote sensors are not likely to detect it from even a low-flying (~500 m above ground level) airborne platform. The necrosis symptom is generally associated with severe levels of foliar injury, whereas chlorosis usually predominates at moderate and light levels.

These reflectance experiments indicate the probable capabilities and limits for detecting SO_2 effects on the foliage of two sensitive, economically important crops in the Tennessee Valley. Experiments to verify these laboratory-based findings by growing and scanning experimental plots of soybeans and wheat are in progress.

This report was submitted by the Tennessee Valley Authority, Office of Natural Resources, in partial fulfillment of Energy Accomplishment Plan 80 BDJ under terms of Interagency Agreement EPA-IAG-E721-DJ with the Environmental Protection Agency. Work was completed as of December 1979.

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SECTION 1

INTRODUCTION

GENERAL

The effects of sulfur dioxide (SO_2) emissions from large coal-fired power plants on vegetation have been recognized as a potential problem for more than a decade. Field observers are seeking better methods for measuring the intensity, geographical distribution, and areal extent of foliar injury. The traditional method for gathering such information is to observe and record injury to SO_2-sensitive indicator species such as ragweed and blackberry. Fixed SO_2 monitoring stations are also used to determine the spatial characteristics of plume contact with the ground. A map illustrating the characteristics of an SO_2 episode is often prepared from the records of field observations and monitors.

Some problems exist with the traditional approach to surveying and identifying SO_2 effects. The network of fixed SO_2 monitors around most coal-fired power plants is often inadequately dense for mapping the exact limits of the plume's contact with the ground. Field botanical surveillance is usually restricted to readily accessible areas because of the requirement to reconnoiter extensive areas quickly. The process of identifying symptoms of foliar injury is complex. Herbicides, lack of essential plant nutrients, and senescence must be considered since they can produce foliar effects similar to those of SO_2.

Remote sensing can assist those engaged in field surveillance of SO_2 effects on crops and trees. The technique provides a permanent record on film or magnetic tape. An aircraft serving as an instrument platform can continuously cover extensive areas, some of which may

be inaccessible to field teams. The coverage can be essentially synoptic rather than spread over a period of several days or more. Perhaps the greatest advantage of remote sensing, in contrast with field observations, is its greater objectivity and consistency of measurements over time and space.

The present state-of-the-art of remote sensing requires that ground truth--field observations--be gathered to support the analysis of the remotely sensed data. In the case of SO_2 effects on vegetation, preliminary but detailed information must be gathered concerning differences in spectral reflectance between the objects of interest (affected foliage) and the background (unaffected foliage). If such information is obtained beforehand, the appropriate sensor configurations, films, filters, scanner channels and bandwidths, and other options may be selected and used.

Spectroradiometry provides information on spectral reflectance characteristics of objects. This report describes the results of a series of laboratory-based experiments in which spectroradiometry was used to obtain spectral curves of visible and near-infrared reflectance of SO_2-affected soybean and wheat plants.

The objective of the research was to determine whether significant differences in spectral reflectance of three SO_2-affected and unaffected crop species could be detected remotely in the laboratory and, if so, to characterize these differences. Followup experiments will be conducted to verify the findings in experimental field plots. The approach of the laboratory research included (1) growing uniform groups of plants in a greenhouse, (2) exposing them in a controlled fashion to SO_2 in a laboratory exposure chamber, (3) systematically observing the foliar effects

of SO_2, (4) scanning the plants with a spectroradiometer while controlling as many of the variables as possible, and finally, (5) statistically analyzing the results to make some soundly based generalizations on changes in spectral reflectance.

The hypothesis is that there is a relationship between reflectance and foliar injury from SO_2. Several statistical tests were made in the search for a relationship; correlation analysis was the primary quantitative technique used.

This document is the second of a two-part series on reflectance. The earlier report[1] describes photometric analysis of aerial photographs to obtain reflectance data from that source.

REVIEW OF THE LITERATURE

Few reports and papers describing the reflectance characteristics of SO_2-affected vegetation have been published. Background information was, therefore, supplemented by reports and papers describing general physiological stress and disease in plants. Regardless of the causative agent, the manifestations of stress exhibit more similarities than differences, and they often result in either foliar necrosis, chlorosis, or a combination of the two symptoms. In our study, the objective was to separate stressed plants from a background of unstressed plants. Because the agent was known beforehand to be SO_2, determination of the identity of the agent was not the problem.

The physical and physiological basis for reflectance from vegetation was summarized recently by Knipling.[2] He pointed out that a typical plant leaf has (1) low reflectance in the visible spectral region because of strong absorption by chlorophylls and (2) high reflectance in the

near-infrared region because of scattering within the leaf and lack of absorption. Beyond 1.3 micrometers (μm) in the infrared, there is relatively low reflectance because of strong absorption by water.

Knipling stated that, when leaves are affected by disease and physiological stress, the greatest change occurs in the visible region rather than the infrared because of the sensitivity of chlorophyll to physiological disturbances.[3] He supported the argument that changes in infrared reflectance are not very reliable for indicating stress in plants.[4] In advanced stages of senescence, the infrared reflectance always decreases, most likely because of the breakdown or deterioration of cell walls.[5] What happens to visible reflectance as a leaf is stressed? Wert[6] measured ponderosa pine foliage that was affected by oxidant air pollution and reported that visible reflectance increased as chlorophyll content decreased. This relationship agrees with empirical data gathered for this report.

A more comprehensive approach is to exploit both the visible and near-infrared spectra. The ratio of near-infrared to red (IR/R) reflectance has received considerable attention in recent years. Many investigators, beginning with Jordan[7] in 1969, have used this ratio to estimate biomass and leaf area index. Colwell[8,9] also found the ratio useful for estimating biomass. Numerous investigators[10,11,12] have recently applied the IR/R ratio to Landsat image analysis for determining range grassland biomass. The ratio is considered to be a measure of relative "greenness" of vegetation.[13] Thus, there is an implication that the IR/R ratio is associated with vegetative vigor or stress as well as canopy density (leaf area index) and, roughly, photosynthetically active biomass. Because the ratio is associated with so many other variables, it cannot be a perfect indicator of stress. However, it appears to be the best available measure.

In summary, the literature contains generally accepted theories describing the internal reflectance mechanism of a leaf and the behavior of the reflectance curve in the visible and near-infrared spectra when a plant is stressed. However, the reports and articles indicate that the actual reflectance curve of a species or variety of plant under stress is not easily predicted. Visible reflectance generally increases with stress. The response of reflectance in the near-infrared is variable, although it eventually decreases in advanced senescence. The IR/R reflectance ratio seems to be favored as a measure of stress, but its value is influenced also by canopy density variations. In remote sensing studies, the stress-causing agent cannot usually be identified without ground truth. Foliar markings, which indicate the identity of the agent, cannot be resolved from the distances or altitudes at which the sensor is operated. However, clusters of stressed plants can often be distinguished from a background of normal plants by using remote sensors.

The spectral reflectance characteristics of SO_2-affected soybeans and winter wheat, in particular, are not found in the literature. A spectroradiometric study is warranted to obtain reflectance data for comparison with observed foliar injury to uncover any relationships that may exist between the two variables.

SECTION 2

CONCLUSIONS

GENERAL

Spectroradiometry is a useful laboratory technique for measuring the changes in spectral reflectance that may be associated with SO_2-induced foliar injury to soybeans [Glycine max (L.) Merr.] and wheat (Triticum aestivum) plants. The results can be used for designing remote sensor acquisition systems; in particular, they can provide guidance for selecting film and filter combinations for aerial multiband cameras and optimum channels for multispectral scanners. However, before the results can be put to practical use, they should be verified by using experimental field plots.

Meaningful but complex relationships exist between reflectance and foliar injury to soybeans and wheat. To ferret out these relationships, we examined the components of injury and bands or regions of reflectance.

SOYBEANS

The necrosis symptom is significantly related ($\alpha = .05$) to the total spectrum of visible and near-infrared (IR) reflectance of soybeans and to certain bands within this spectrum (Table 1). When the mean reflectances of necrotic soybeans and unaffected soybeans are compared, these differences are found. Red (650 nm) reflectance is the best indicator of necrosis ($r = +0.98$). There is apparently no relationship between the chlorosis symptom and reflectance of soybeans.

TABLE 1. SPECTRAL DISCRIMINATION OF SO_2-AFFECTED SOYBEANS

Foliar symptom	Total reflectance spectrum	Blue	Green	Red	IR	IR/R
Chlorosis						
Necrosis	X		X	X	X	

X indicates a statistically significant (α = .05) difference exists between mean reflectances of classes of unaffected and SO_2-affected soybeans, as determined by an analysis of variance.

WINTER WHEAT

Measurements of either the total visible reflectance spectrum or any of the three individual bands can be used to distinguish unaffected or lightly affected wheat from severely affected wheat (Table 2). However, the measurements cannot be used to distinguish moderately affected wheat from severely affected wheat. Of the individual bands, the green proved best ($r = +0.90$) for detecting chlorosis, and the red band was best ($r = +0.85$) for detecting necrosis. No individual bands offered any advantage over the total visible spectrum. All relationships were positive; that is, increases in visible reflectance corresponded to increases in foliar injury. Near-infrared reflectance of wheat was not measured.

TABLE 2. SPECTRAL DISCRIMINATION OF SO_2-AFFECTED WINTER WHEAT

Foliar symptom	Total reflectance spectrum	Blue	Green	Red	IR	IR/R
Chlorosis	X	X	X	X	*	*
Necrosis	X	X	X	X	*	*

X indicates a statistically significant (α = .05) difference exists between the mean reflectance among classes of unaffected and SO_2-affected wheat, as determined by an analysis of variance.
* indicates not measured.

SUMMARY

The soybean results indicate that, unless the SO_2 injury includes the necrosis component, reflectance-measuring remote sensors such as aerial cameras and multispectral scanners are not likely to detect it, even from low altitudes (~500 m above ground level). Necrosis predominates at higher levels of injury to soybean foliage, whereas chlorosis predominates at low and intermediate levels. Chlorosis is a sometimes subtle yellowing of the foliage that is often difficult to detect, even at close range in the field.

Both chlorosis and necrosis in winter wheat should be detectable with airborne remote sensors that measure the total visible reflectance spectrum. Those that are sensitive to the green wavelengths should detect chlorosis best, and those sensitive to red wavelengths should detect necrosis best.

SECTION 3

RECOMMENDATIONS

The conclusions from this study have led to the following recommendations for future research in spectroradiometry of SO_2-affected vegetation:

1. Reflectances of soybean and winter wheat plants that are grown in experimental field plots and exposed to controlled doses of SO_2 should be measured and characterized. Results described in this report indicate that such controlled experiments should precede reflectance measurements of field crops that are affected by actual SO_2 emissions.
2. Reflectances of SO_2-affected tree seedlings and saplings should be characterized and compared with reflectances of unaffected trees. Acquisition and analysis of these data are recommended because of the importance of forest products. The visual symptoms of many trees are similar to those plants investigated in this study, and success in remote sensing is therefore predicted.
3. The information obtained by spectroradiometry should be used for planning remote sensor overflights of SO_2-affected areas wherever they occur. The spectral reflectance data should also be useful to those who plan instrumented overflights of vegetation that is otherwise physiologically stressed or diseased.
4. Field testing of the OMA 2 spectroradiometer leads us to recommend a procedure of systematic spot measurements over noncontiguous agricultural fields from a helicopter rather than the continuous-strip acquisition by an airplane. The

latter technique was practiced by NASA when they used a similar instrument.[14] The characteristic geographic pattern of SO_2-affected agricultural fields in the Tennessee Valley region is so discontinuous that the system of spot measurements is more efficient for acquiring reflectance data. Future reports will describe our aerial remote sensing operations in detail.

SECTION 4

METHODS AND INSTRUMENTS

INSTRUMENTATION

Two dissimilar telespectroradiometers (TSR) were used to scan the plants. We began the project with a conventional instrument and later acquired a new, state-of-the-art multichannel TSR. Both TSR's provided spectral curves of reflectance versus wavelength.

The conventional TSR was used to scan the wheat plants. It is a Gamma Scientific Model 3100/3400 system. Its slow scan speed (20 seconds or longer) was not a problem in the laboratory. Spectral coverage was from 400 to 700 nanometers (nm) in the visible channel. A separate, cooled optical head was used to scan the red and infrared spectrum from 600 to 1000 nm. Unfortunately, the two heads could not be used simultaneously. Output was in radiance units (microwatts per square centimeter per steradian per nanometer) and the system has a 4-nm spectral resolution. We used either a 3- or 1-degree telescope field of view (FOV). The same telescope and FOV's were used with the other TSR, described below.

The TSR used to scan the soybeans has an optical multichannel detector. It is a microprocessor-controlled optical system that we adapted to remote sensing in the laboratory and field. Application of optical multichannel TSR's to the natural sciences has been very rare.[15] We used an Optical Multichannel Analyzer (OMA 2) manufactured by Princeton Applied Research Corporation.[16] Figure 1 illustrates the configuration of our system; Appendix A provides details and specifications of the components. Scanning is essentially instantaneous (total scan time = 0.7 ms), and data storage is on flexible disc.

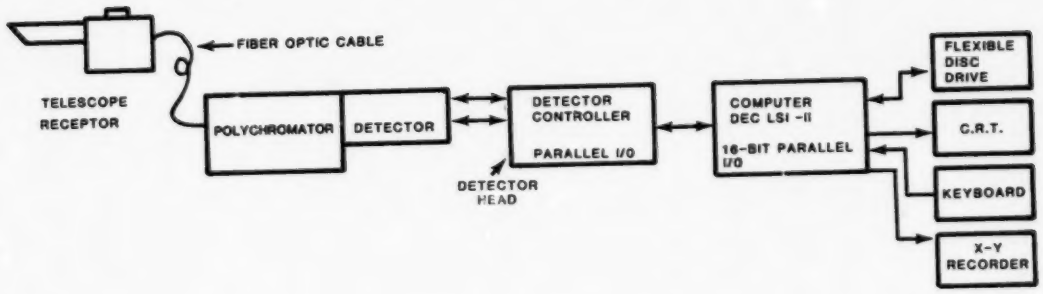


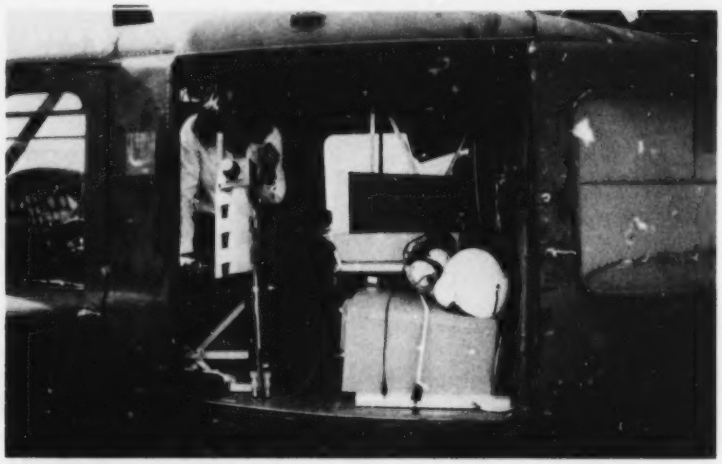
Figure 1. OMA 2 system configuration for scanning vegetation from aircraft, van, and laboratory bases.

Figure 2 illustrates the scanning operation in the laboratory, van, and helicopter. This study concerns only laboratory-based experiments.

The OMA 2 operation is unique because it accumulates scans, integrating them over a pre-selected time frame or number of scans. Such accumulation improves the signal-to-noise ratio and averages out short-term variations caused by movement of foliage by wind as well as inadvertent movements (jitter) of the instrument platform during scanning. The shape of a spectral curve from an ordinary slow-scan TSR would be distorted by these short-term movements.

The vidicon detector of the OMA 2 is sensitive to a broad range of visible and near-infrared wavelengths (Figure 3). The coverage of our system is restricted to a spectrum that is 337 nm wide, but the center of the scanned spectrum can be positioned anywhere within the range of detector sensitivity. For the soybeans, we selected a range of 430 to 767 nm, which included the green chlorophyll peak, the red chlorophyll absorptance region, and part of the near-infrared reflectance plateau. The spectral resolution of the system is about 2 nm, being limited in our case by the size of the input slit to the spectrometer, the diameter of the fiber optics bundles, and our success in aligning the optical components before each set of measurements.

The intensity scale (y-axis) of the OMA 2 video monitor reads in counts per channel. We scanned 500 discrete channels at the 140-μs/channel rate. The y-axis was calibrated by scanning a lamp having a known spectrum. Background subtraction, statistical grouping, and averaging of curves was done on the console keyboard, after which the curves were stored on flexible discs.



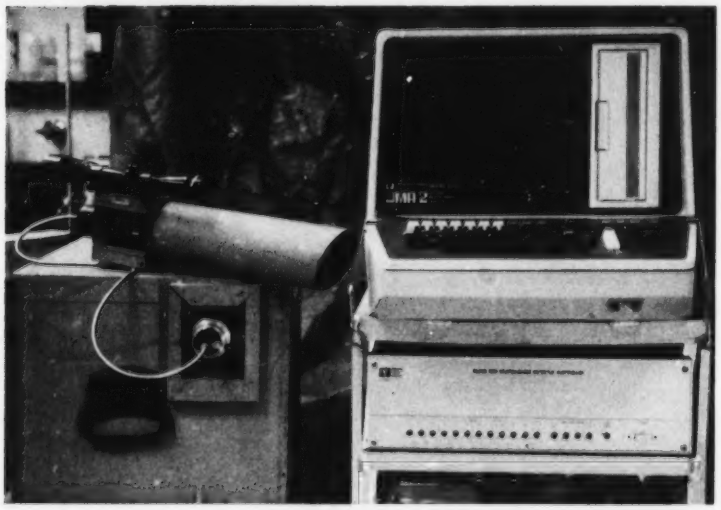


Figure 2. OMA 2 system in helicopter, van, and laboratory.

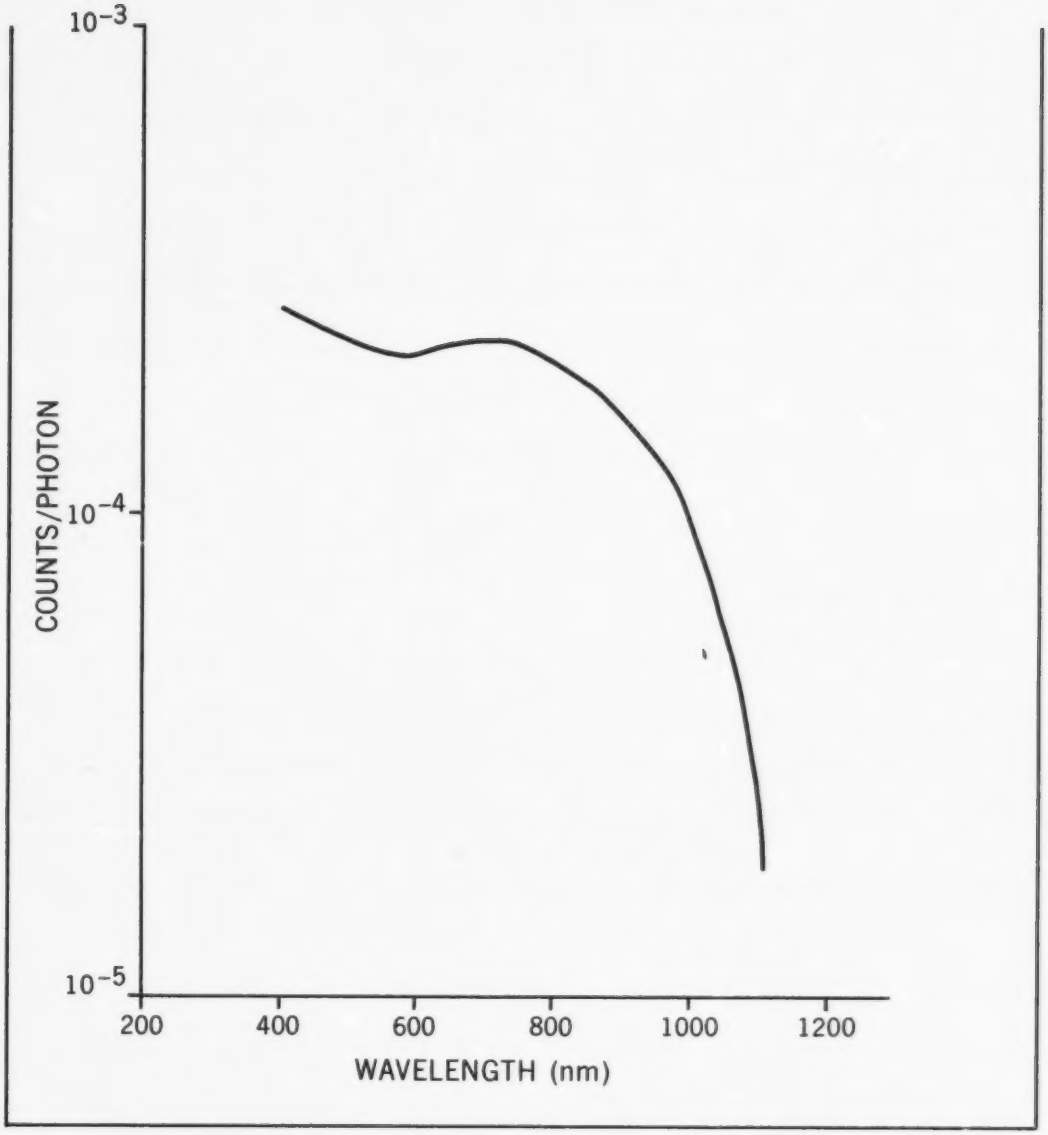


Figure 3. Typical spectral response of Model 1252E infrared-enhanced silicon-vidicon detector (data from Princeton Applied Research Corporation).

CONCEPTS OF RADIANCE AND REFLECTANCE

The term "reflectance" describes the ratio of radiant energy reflected from a surface to that incident upon it. Reflectance cannot be measured directly, but can be computed from measurements of radiant energy. The shape of the radiance curve obtained is a function of three wavelength-dependent parameters: (1) variation of the intensity of illumination; (2) variation of the reflected energy; and (3) variation in sensitivity of the detector. If parameter (2) is to be isolated from parameters (1) and (3), a standard surface with an established reflectance curve should be used. This curve may then provide the basis for normalizing radiance curves.

CURVE NORMALIZATION

Spectral curves were normalized using the procedure outlined in Appendix B to convert them from radiant energy units to percent reflectance. The instrument used to scan the soybeans had an integral LSI-11 minicomputer, which was used to store, process, and manipulate the curves. The instrument used to scan the wheat had an analog output. These curves were digitized separately on the graphics tablet of a Tektronix 4014 graphics terminal; they were then normalized, averaged, and otherwise manipulated and stored using an IBM 370 computer accessed through a remote terminal. A standard 18-percent-gray reflecting surface, which was one of a set of panels borrowed from the NASA Earth Resources Laboratory in Slidell, Louisiana. This panel is hereafter referred to as the NASA gray target. A reflectance curve was supplied with the target. For convenience, a small (20- by 25-cm), 18-percent-gray card was calibrated against the NASA gray target for

day-to-day use in the laboratory and field. The gray card is hereafter referred to as the TVA reference standard; it was scanned along with the vegetation to provide a basis for curve normalization.

EXPERIMENTAL DESIGN

Plants

Soybean (Glycine max [L.] Merr. var Cutler) and winter wheat (Triticum aestivum [L.] var Coker 68-15) plants were grown to maturity in a greenhouse. Each step in the procedure was carefully controlled to assure uniform groups of plants. Registered seed was used to guarantee varietal purity. The soil mixture consisted of specific proportions of Decatur soil (75 percent by weight), sand (20 percent by weight), and peat (5 percent by weight) with nitrogen, phosphorus, and potassium nutrients added and the pH adjusted to 6.5. Natural illumination was supplemented in the greenhouse with General Electric MV-1000/U 1000-watt mercury vapor metal halide lamps. The period of illumination was adjusted by timers to match the increasing day length. The positions of the pots were changed several times a week to compensate for variations in illumination. Watering was carefully controlled on a pot-by-pot basis by weighing the pots daily and adding water to maintain the moisture content of the soil at 20 percent.

Groups of plants were exposed to SO_2 in a controlled exposure chamber for specific doses to create the foliar effects. After exposure, the plants were returned to the greenhouse, and the effects gradually appeared. Observations of chlorosis and necrosis were made a week after exposure to assure that all the effects had developed.

Scanning Procedure

All scanning was done in the laboratory under carefully controlled illumination. Individual soybean leaflets and wheat canopies were scanned. The lamps were carefully oriented to minimize the specular (glare) component of radiation into the telescope. This was done for wheat and soybeans by maintaining a 45-degree angle between the telescope axis and the tungsten-halogen (3200 kelvins) type DYH lamps. The distance between telescope and plant was determined by selecting a telescope FOV of 1 or 3 degrees and filling the FOV with foliage to minimize the contribution of the background. Overhead views of the wheat canopies were obtained by orienting the top of the plant container so that it was perpendicular to the telescope axis. When an individual soybean leaflet was scanned, its surface was mounted flat on a board that was perpendicular to the telescope axis. Soybean leaflets were detached and scanned immediately after the observations were recorded. The wheat plants were scanned, pot by pot, after visual observation and scoring was completed.

Analysis of Soybeans

Groups of soybeans were exposed to one of several SO_2 doses that were chosen to create a wide range of foliar effects. The peak concentrations and durations of exposure were (1) 15720 $\mu g/m^3$ for 0.50 and 0.67 h and (2) 10480 $\mu g/m^3$ for 0.75 and 1.25 h. A total of 153 leaflets was scanned. The selection was made by determining which nodes were affected on the most severely affected plants and then including the leaflets growing on these nodes on all plants. The unaffected leaflets on those nodes were also included. The spectral reflectance curves were

grouped in broad classes by level of injury. A mean curve was computed for each class or combination of classes to show trends in the relationship between foliar effects and reflectance. Analysis of variance was used to determine whether differences among classes were statistically significant. This analysis was done for specific wavelengths: blue (450 nm), green (550 nm), red (650 nm), and infrared (750 nm). The statistical analysis included the two components of foliar injury, chlorosis and necrosis. F-tests were used to determine significance of differences in reflectance between injury classes.

Analysis of Winter Wheat

Winter wheat plants were exposed to five levels of SO_2 in the controlled exposure chamber to create a wide range of foliar effects. The SO_2 concentrations (all 3-h averages) used were 0, 3930, 5240, 6550,7860, and 9170 $\mu g/m^3$. After exposure, the plants were returned to the greenhouse to allow the effects to develop. A week later, the plants were observed systematically, pot by pot, to obtain statistics on the chlorosis and necrosis components. Effects ranged from none for the control group to "very severe" for the groups receiving 6550, 7860, and 9170 $\mu g/m^3$ SO_2.

When observations were complete, spectral scanning began. The near-infrared curves were obtained with a separate optical head. No useful near-infrared scans of wheat were obtained because of problems in calibration. These problems have since been solved by substituting the OMA 2 TSR for the Gamma Scientific model. The near-infrared curves obtained for wheat were not statistically analyzed because apparent variation was slight--typically less than 2 percent.

Correlation analysis and one-way analysis of variance were performed on the wheat data. The latter procedure focused on differences among injury classes. F-tests were used to determine significance ($\alpha = .05$).[18] This analysis was done for three specific wavelengths of reflectance--blue (450 nm), green (550 nm), and red (650 nm).

SECTION 5

RESULTS AND DISCUSSION

SOYBEANS

Descriptive statistics for foliar injury (chlorosis and necrosis) were obtained using traditional class boundaries used by TVA in field surveillance of SO_2 effects (Table 3).

The individual reflectance curves for soybeans were arithmetically averaged to produce a mean curve for each class of chlorosis and necrosis (Figures 4 and 5).

Some of the averaged reflectance curves for chlorosis (Figure 4) show more separation than others. Chlorosis class 4 (very severe injury) has the highest visible and lowest near-infrared (IR) reflectance of all. However, the other classes are not separable at any wavelength.

The averaged reflectance curves for necrosis show more differences among classes than those for chlorosis (Figure 5). The greatest separation is in the red wavelengths (chlorophyll absorption band), at about 650 nm. The curves stack up in order, with curve 0 (control) having the lowest reflectance at all wavelengths. Class 3 (>25 percent necrosis) shows relatively high green and red (R) reflectance and a relatively low IR reflectance, as predicted. In fact, the IR reflectance is lower for class 3 than for all other classes.

The possibility of a relationship between the total area (cm^2) beneath each spectral curve and injury to soybeans was investigated. Correlation revealed a simple correlation coefficient (r) of only +0.47 between curve area and percent chlorosis, but a higher r value (+0.92) was found between

TABLE 3. DATA CLASSES AND FOLIAR EFFECTS OF SO_2 ON SOYBEANS

Chlorosis					Necrosis				
Qualitative level of injury	Class	Range (%)	Mean injury (%)	No. of leaflets	Qualitative level of injury	Class	Range (%)	Mean injury (%)	No. of leaflets
None	0	0	0	7	None	0	0	0	7
Light	1	1-10	6.5	52	Light	1	1-10	6.9	15
Moderate	2	11-25	15.6	20	Moderate	2	11-25	21.7	3
Severe	3	26-50	39.3	29	Severe and very severe	3	>25	50.0	3
Very severe	4	>50	69.3	26					28
				134					

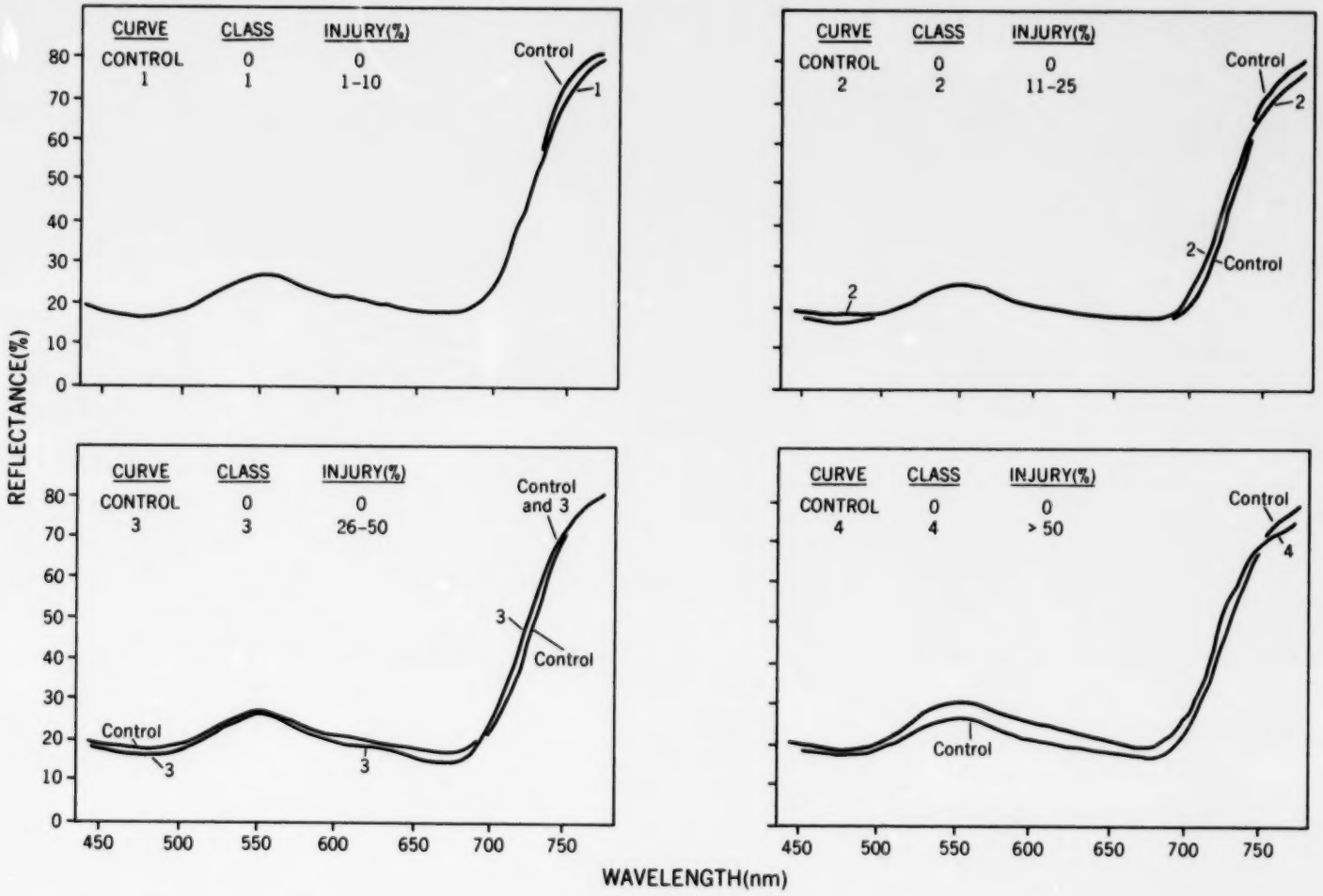


Figure 4. Mean spectral curves for classes of chlorosis in soybeans exposed to SO_2.

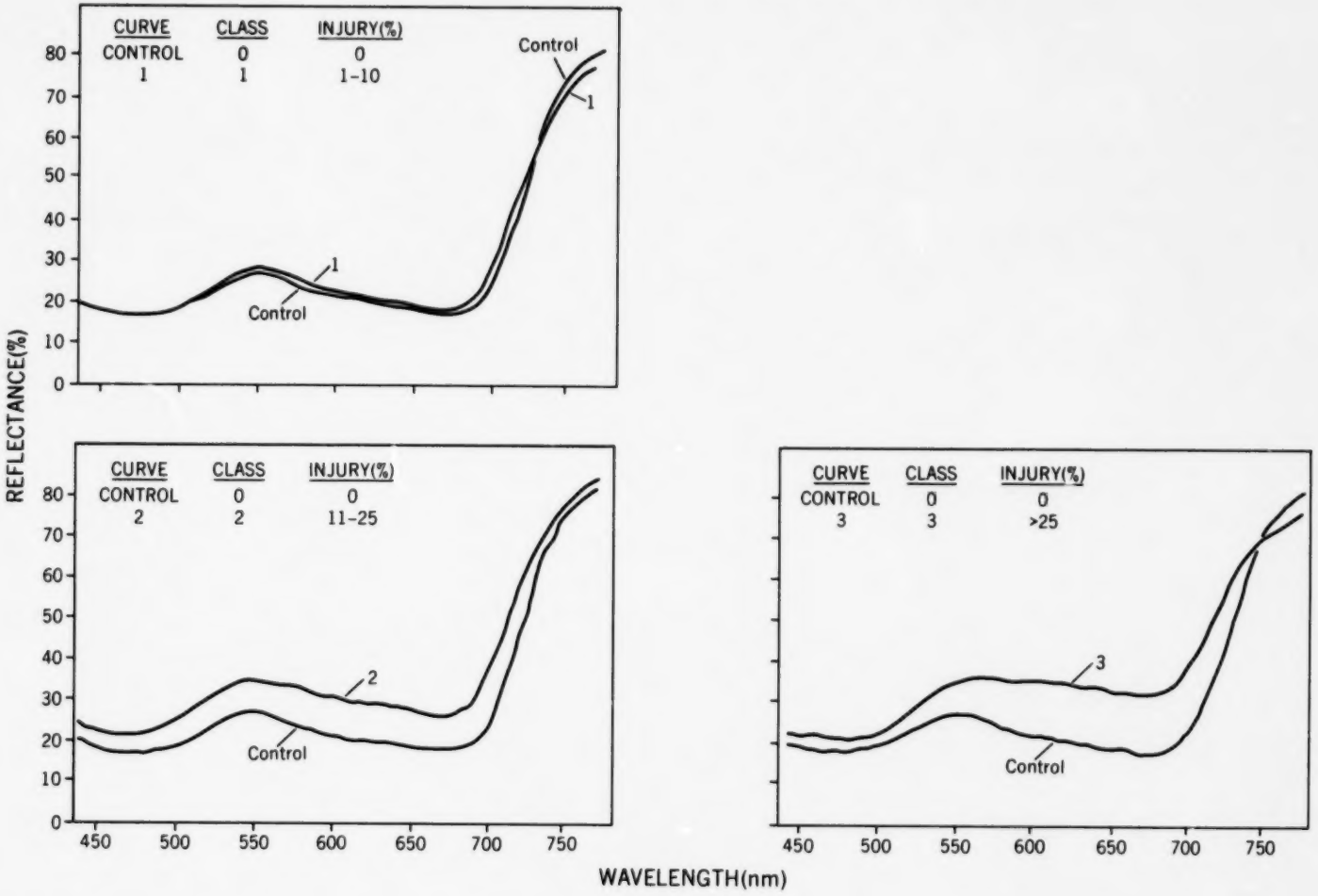


Figure 5. Mean spectral curves for classes of necrosis in soybeans exposed to SO_2.

curve area and percent necrosis. Obviously, the shape of a curve can change without affecting its total area, and this fact led to the scrutiny of shifts in reflectance at particular wavelengths.

The changes in reflectance at four particular wavelengths, each representing the approximate midpoint (4-nm interval) of a spectral region, were studied. These intervals were blue (450 nm), green (550 nm), red (650 nm), and IR (750 nm). The IR to R ratio was also calculated and studied. The reflectance means and standard deviations for each injury class are given in Table 4. The strengths of the relationships between reflectance and injury are indicated by correlation coefficients (Table 5). This table warrants some explanation. The correlations between reflectance and the chlorosis component of injury are quite low in comparison to those between reflectance and necrosis. The blue, green, and red bands appear to be useful indicators of necrosis. The IR band seems useless. The IR/R ratio offers no improvement over the red band alone. The correlation coefficients can be high but still not statistically significant, so further statistical analysis was done, including an analysis of variance.

The purpose of the analysis of variance was to determine whether differences in the means of reflectance for the injury classes were statistically significant. The results revealed that there was no significant ($\alpha = .05$) difference in the reflectance of chlorotic and unaffected soybeans at any of the four wavelengths tested. There was also no significant difference in the IR/R ratio (Appendix C).

For necrosis, the results were more positive. Because the necrosis classes were small in size, they were combined and compared to the

TABLE 4. REFLECTANCE STATISTICS FOR CLASSES OF SO_2-AFFECTED SOYBEANS

Necrosis class[a]	Mean Reflectance (%) ± Standard Deviation				IR/R
	Blue	Green	Red	IR	
0 (0% injury)	18.51 ± 6.18	28.60 ± 7.46	18.31 ± 7.88	75.40 ± 8.28	4.12
1 (1-10%)	17.30 ± 6.55	27.39 ± 8.97	19.59 ± 10.96	67.18 ± 2.69	3.43
2 (11-25%)	21.56 ± 8.08	34.26 ± 9.31	27.90 ± 11.06	73.29 ± 5.03	2.63
3 (>25%)	22.64 ± 2.88	36.35 ± 3.65	34.60 ± 6.25	71.98 ± 0.06	2.08
Chlorosis class[b]	**Mean Reflectance (%) ± Standard Deviation**				**IR/R**
	Blue	Green	Red	IR	
0 (0% injury)	18.31 ± 4.88	27.90 ± 6.04	19.14 ± 6.90	75.00 ± 6.57	3.92
1 (1-10%)	19.21 ± 6.96	28.53 ± 8.22	19.60 ± 2.18	73.27 ± 33.43	3.74
2 (11-25%)	19.30 ± 7.24	29.05 ± 8.71	19.71 ± 8.99	74.03 ± 7.50	3.76
3 (26-50%)	17.28 ± 5.95	27.61 ± 7.99	17.23 ± 8.99	75.09 ± 8.68	4.36
4 (>50%)	18.88 ± 5.58	31.73 ± 6.37	21.35 ± 7.83	73.79 ± 7.23	3.46

[a]For necrosis, 1-10% represents light injury; 11-25%, moderate; and >25%, severe.
[b]For chlorosis, the added classes (3 and 4) represent severe injury.

unaffected class. There was a significant (α = .05) difference in the means of green reflectance of the unaffected soybeans (class 0) and soybeans exhibiting moderate or greater necrosis (>11 percent). The same findings were obtained for red reflectance. There was a significant difference in IR reflectance of the unaffected soybeans and the necrotic soybeans (combination of classes 1, 2, and 3). No other significant differences in reflectance were found (Appendix C).

TABLE 5. SIMPLE CORRELATION COEFFICIENTS FOR REFLECTANCE AND FOLIAR INJURY TO SOYBEANS

	Blue	Green	Red	IR	IR/R
Chlorosis	0.20	0.72	0.36	-0.10	-0.32
Necrosis	0.89	0.92	0.98	0.00	-0.94

WINTER WHEAT

The wheat was divided into six groups, five of which were exposed to different concentrations of SO_2 for 3 h in the chamber. One group was used for control. The range of foliar symptoms was broad, consisting primarily of necrosis (Table 6).

The scanning procedure yielded normalized curves showing an increase in overall reflectance that corresponded to increasing foliar injury (Figure 6). Correlation analysis revealed an r value of 0.85 between curve area and percent chlorosis in wheat. A closer association (r = 0.92) emerged between curve area and percent necrosis. All relationships were positive; curve area increased with injury level. Next, curve area and SO_2 dose ($\mu g/m^3$) were compared, yielding an r of 0.92. This relationship was also positive in direction.

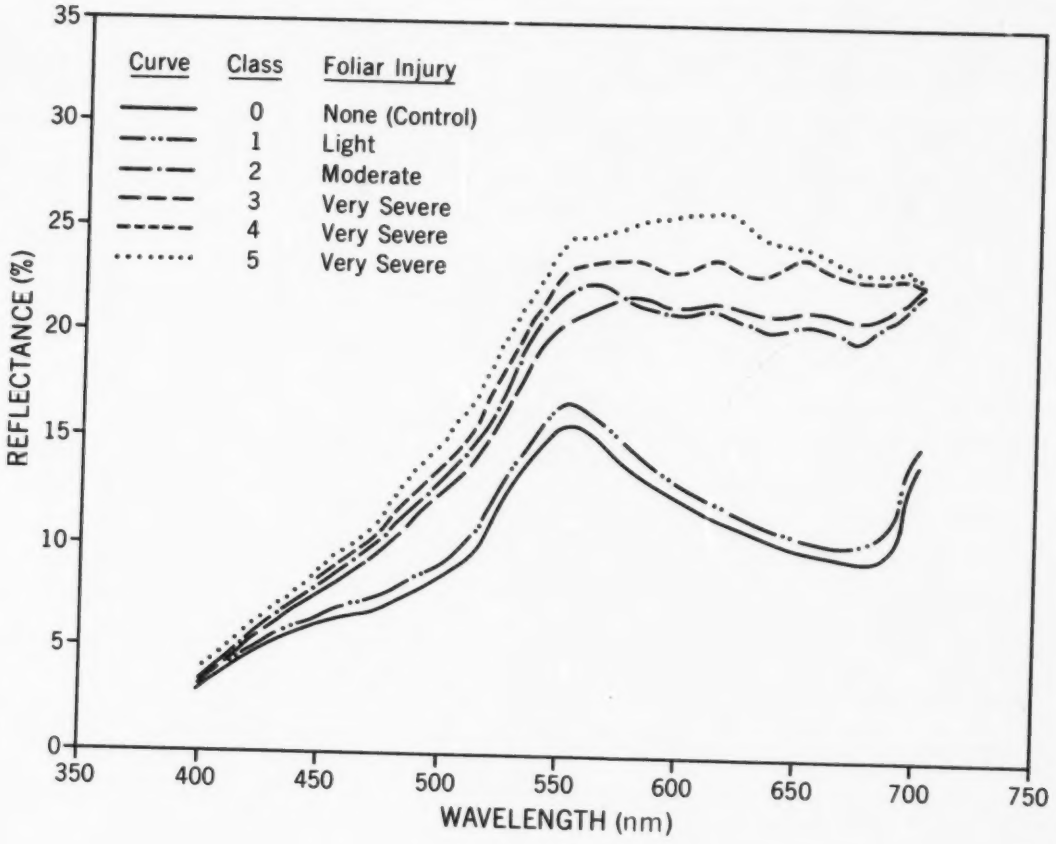


Figure 6. Mean spectral curves for classes of unaffected and SO_2-affected winter wheat.

TABLE 6. DATA CLASSES AND FOLIAR INJURY TO WINTER WHEAT FROM SO_2

Qualitative level of effects[a]	Dose Class	No. of pots	Foliar injury		SO_2 concentration, 3-h avg ($\mu g/m^3$)
			Mean chlorosis (%)	Mean necrosis (%)	
None	0	6	0	0	0 (control)
Light	1	4	1	2	3930
Moderate	2	2	1	22	5240
Very severe	3	4	4	50	6550
Very severe	4	3	5	56	7860
Very severe	5	2	5	76	9170

[a]Where light injury is <10 percent; moderate, 11-25 percent; severe, 26-50 percent; and very severe, >50 percent.

The change in reflectance in blue, green, and red wavelength regions was also studied (Table 7). The red (650 nm) reflectance increased with increasing stress; this rise was particularly evident at moderate and severe levels of stress. Green (550 nm) peak reflectance also increased, but was more evident at light levels of stress (Figure 6).

Statistical analysis of blue, green, and red reflectance for winter wheat yielded positive r coefficients ranging between 0.73 and 0.90 (Table 8). Near-infrared reflectances of wheat were also measured, but they showed no relationship to injury.

TABLE 7. REFLECTANCE STATISTICS FOR CLASSES OF SO_2-AFFECTED WINTER WHEAT

Necrosis class[a]	Mean Reflectance (%) ± Standard Deviation		
	Blue	Green	Red
1 (0% injury)	6.4 ± 0.7	16.2 ± 2.0	10.3 ± 2.0
2 (1-25%)	7.3 ± 0.4	17.6 ± 1.7	12.4 ± 3.1
3 (26-50%)	7.9 ± 0.6	21.1 ± 2.6	21.6 ± 3.1
4 (>50%)	8.7 ± 0.6	23.7 ± 0.5	24.3 ± 1.4
Chlorosis class[b]	**Mean Reflectance (%) ± Standard Deviation**		
	Blue	Green	Red
1 (0% injury)	6.4 ± 0.7	16.2 ± 2.0	10.3 ± 2.0
2 (0.1-1%)	7.7 ± 0.6	20.2 ± 3.2	19.0 ± 5.8
3 (>1%)	8.4 ± 0.9	21.9 ± 2.7	20.3 ± 5.7

[a]For necrosis, 1-25% represents light/moderate injury; 26-50%, severe; and >50%, very severe.
[b]For chlorosis, all three classes represent very light injury.

TABLE 8. SIMPLE CORRELATION COEFFICIENTS FOR SINGLE-BAND REFLECTANCE AND FOLIAR INJURY TO WINTER WHEAT

	Reflectance		
	Blue	Green	Red
Chlorosis	+0.83	+0.90	+0.81
Necrosis	+0.73	+0.83	+0.85

A one-way analysis of variance showed that significant (α = .05) differences in mean blue, green, and red reflectance existed among all classes of chlorosis and necrosis (Appendix C). Trends confirmed that increasing blue, green, and red reflectance was associated with increasing chlorosis and necrosis in wheat.

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APPENDIX A

SPECIFICATIONS OF OPTICAL MULTICHANNEL AND CONVENTIONAL PHOTOMULTIPLIER TSR SYSTEMS

SPECIFICATIONS OF OPTICAL MULTICHANNEL TSR SYSTEM

SYSTEM DESCRIPTION

The OMA 2 Optical Multichannel Analyzer is a microprocessor-controlled multichannel optical detector and visual display system consisting of the 1215 console, 1216 detector controller, 1252E detector, and components adapted by TVA, including a telescope, a fiber-optic cable and faceplate, and an x-y recorder.

Component	Specifications
Console, model 1215	
Front panel	84-key keyboard, 41-cm diagonal display, flexible disc drive (IBM compatible format)
Rear panel	Analog recorder output
Memory system	Monostore XI/Planar LSI-11 16K x 16 memory assembly by Monolithic Systems Corporation; signal interface through DEC LSI-11 I/O bus
RAM data storage	4K single precision, 2K double precision
Disc storage	Operating system plus 100 spectral curves of 500 double precision points each
Arithmetic functions	+, -, ÷, natural log, and decimal log; constants, powers, and roots on full curves; arithmetic functions are formatted in algebraic notation with parenthesis capability for seven reference curves and recursive operation up to disc capacity.
Power input	115/230 V ± 10 percent, 50/60 Hz, 450 watts
Dimensions	44.86 cm W x 72.72 cm D x 39.27 cm H
Unit weight	50 kg
Spectrometer, model 1225 (Jobin Yvon M25 grating monochromator)	Focal length 0.25 m, aperture f/3, holographic grating, 152.65 grooves/mm, blazed at 2 μm, input slits, 2 available, 0.25 mm or 0.90 mm wide

Component	Specifications
Detector, model 1252E (IR-enhanced)	Silicon-vidicon target, sensitivity 2400 photons/count at 600 nm, background noise 1.5 counts rms max., full-scale 16,383 counts/channel/frame, dynamic range 1 x 10^4 min, linearity as a function of intensity ± 1 percent, scanned area 12.5 x 12.5 mm, useful spectral range 350 to 1100 nm (scan width restricted to 337 nm band)
Detector controller, model 1216	16-bit computer peripheral, frame scan time 10 to 70 ms, channel time 20 to 140 μs, number of channels scanned 2 to 512/track, number of tracks 1 to 256, power input 115/230 V ± 10 percent, 50/60 Hz, 14 watts, dimensions 44.2 cm W x 46.7 cm D x 13 cm H, unit weight 15.5 kg
Fiber optic interface, model 1225Q	152.4 cmL x 0.1 mm D (input slit, output circle), quartz fiber optics bundles, adaptor faceplate connects cable to polychromator
X-Y recorder	Hewlett-Packard Model 2D-2
Telescope	Gamma Scientific, Inc., Model 2020-31 f 2.8, focal length 190 mm, selectable angles of view 3°, 1°, 20', 6'
Calibration lamps	Pen-Ray Krypton 760-nm line; Pen-Ray low-pressure mercury vapor 436-, 546-, 579-nm lines

SPECIFICATIONS FOR CONVENTIONAL PHOTOMULTIPLIER TSR SYSTEM

SYSTEM DESCRIPTION

The conventional TSR is a scanning spectroradiometer adapted to a telescope receptor. Photomultiplier-type detectors are used, one for the near-infrared and another for the visible. The system was manufactured by Gamma Scientific, Inc., during the late 1960's.

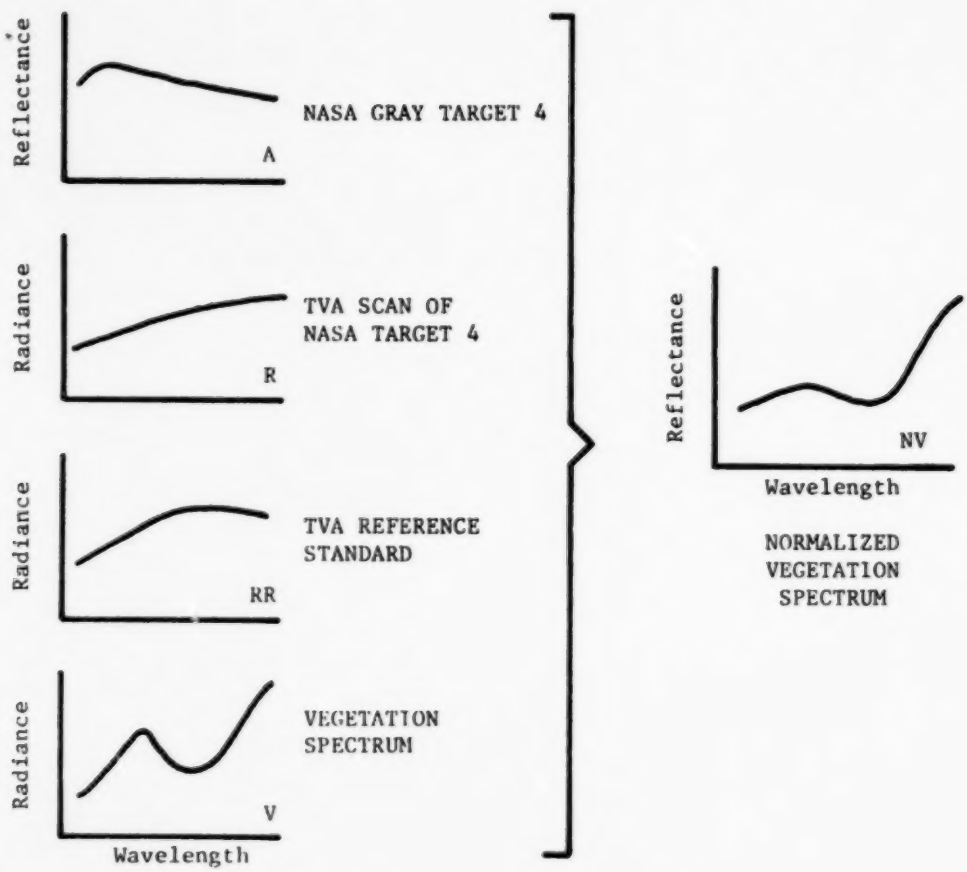
Component	Specifications
Detector heads	Model 3100, S-20 PMT, 400 to 700-nm coverage; model 3400, S-1 PMT (cooled), 600-1000-nm coverage; both heads: max. sensitivity 1 mw/cm^2·nm full scale, flat response ± about 2 percent, wavelength accuracy ± 2.5 nm, half-power bandwidth 4 nm, scan time $\geq$ 20 s, calibrator, internal lamp reference (incandescent), diffraction grating
Power/control unit, model 3100	
Telescope, model 2020-31	f 2.8, focal length 190 mm, selectable angles of view 3°, 1°, 20', 6'; Leupold Vari-XIII 2.5-8x rifle scope adapted to telescope
Fiber optic connecting cable, model 700-3E	Length 46 cm, input diameter 3.2 mm, output slit 10 x 0.9 mm
Recorder, model 500 X-Y	Analog
Unit weight of system	21.2 kg
Dimensions	heads (2) 47 x 17 x 30 cm; control unit 27 x 24 x 23 cm; x-y recorder 45 x 27 x 20 cm
Power requirements	95-125 VAC, 50-60 Hz, current drain ~200 W

APPENDIX B

PROCEDURE FOR NORMALIZING RADIANCE CURVES

APPENDIX B

PROCEDURE FOR NORMALIZING RADIANCE CURVES



(1) One-time procedure to generate absolute curve (C):

$$C = (RR \cdot A)/R$$

(2) Subsequent procedure to produce normalized curves of vegetation (NV):

$$NV = (V \cdot C)/RR$$

APPENDIX C

RESULTS OF ONE-WAY ANALYSIS OF VARIANCE

APPENDIX C

RESULTS OF ONE-WAY ANALYSIS OF VARIANCE FOR SOYBEANS

Chlorosis

Reflectance Band	Class	$\bar{x}$[a]	s[a]	df	F	Significant (α = .05)
Blue	0	7269	1938	4,135	0.39	No
	1	7660	2709			
	2	7762	2883			
	3	7039	2439			
	4	7691	2215			
Green	0	50976	11029	4,135	0.94	No
	1	54020	15642			
	2	55141	15936			
	3	53521	15434			
	4	59767	11554			
Red	0	54650	19698	4,135	0.38	No
	1	58607	26888			
	2	58658	29359			
	3	53267	27498			
	4	61690	26241			
IR	0	272670	23899	4,135	0.50	No
	1	271735	29836			
	2	276752	27771			
	3	280978	33952			
	4	273767	27122			
IR/R	0	5.48	1.79	4,135	1.08	No
	1	5.56	2.30			
	2	5.81	2.59			
	3	6.36	2.52			
	4	5.12	1.90			

[a]Measurement for $\bar{x}$ and s in counts, except IR/R ratio

APPENDIX C

RESULTS OF ONE-WAY ANALYSIS OF VARIANCE FOR SOYBEANS

Necrosis

Reflectance Band	Class	$\bar{x}^a$	s^a	df	F	Significant (α = .05)
Blue	0	7.269×10^3	1.794×10^3	1,25	0.83	No
	1+2+3	8.595×10^3	2.141×10^3			
Green	0	5.098×10^4	1.021×10^4	1,25	1.80	No
	1+2+3					
Green	0	5.098×10^4	1.021×10^4	1,10	4.94	Yes
	2+3	6.647×10^4	1.173×10^4			
Red	0	5.465×10^4	1.824×10^4	1,25	1.93	No
	1+2+3	8.554×10^4	2.599×10^4			
Red	0	5.465×10^4	1.824×10^4	1,10	7.34	Yes
	2+3	9.133×10^4	2.456×10^4			
Infrared (IR)	0	2.727×10^5	2.213×10^4	1,25	4.93	Yes
	1+2+3	2.617×10^5	8.362×10^3			
Infrared (IR)	0	2.727×10^5	2.213×10^4	1,10	0.30	No
	2+3	2.661×10^5	1.234×10^4			
IR/R	0	5.48	1.66	1,25	0.49	No
	1+2+3	3.66	1.27			
IR/R	0	5.48	1.66	1,10	5.96	No
	2+3	3.21	1.11			

[a] $\bar{x}$ and s data in counts, except IR/R ratio

APPENDIX C

RESULTS OF ONE-WAY ANALYSIS OF VARIANCE FOR WINTER WHEAT

	Class	$\bar{x}^a$	s^{2a}	df	F	Significance (α = .05)
	Necrosis					
Blue reflectance, %	1	6.4	.44			
	2	7.3	.17	3,17	13.92	Yes
	3	7.9	.37			
	4	8.7	.32			
Green reflectance, %	1	16.2	4.14			
	2	17.6	2.89	3,17	16.78	Yes
	3	21.1	6.78			
	4	23.7	.25			
Red reflectance, %	1	10.3	3.86			
	2	12.4	9.62	3,17	36.44	Yes
	3	21.6	9.68			
	4	24.3	1.84			
	Chlorosis					
Blue reflectance, %	1	6.4	.44			
	2	7.7	.36	2,18	10.45	Yes
	3	8.4	.78			
Green reflectance, %	1	16.2	4.14			
	2	20.2	10.22	2,18	6.41	Yes
	3	21.9	7.20			
Red reflectance, %	1	10.3	3.86			
	2	19.0	33.57	2,18	6.54	Yes
	3	20.3	32.76			

[a] = $\bar{x}$ and s^2 data in percent reflectance